RESULTS OF X-RAY AND OPTICAL MONITORING OF SCO X-1

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Abstract

Sco X-1 was monitored at optical and X-ray wavelengths from 1970 April 26 to 1970 May 21. The optical observations were made at six observatories around the world and the X-ray observations were made by the Vela satellites. There was a tendency for the object to show greater variability in X-ray when the object is optically bright. A discussion of the intensity histograms is presented for both the optical and X-ray observations. No evidence for optical or X-ray periodicity was detected.

I. Introduction

In April and May of 1970, six observatories around the world took part in a cooperative effort to monitor the optical variations of the object identified with Sco X-1. During the same period of time, the Vela 5A, 5B, 6A and 6B spacecraft monitored the X-ray flux from the source. The observers and institutions participating and the apparatus used are listed in Table I. A schedule of the monitoring carried out by the various observers and the resulting X-ray and optical data overlaps is shown in Figure 1. The duration of this program was 600 hours. Of this time, 225 hours (≃37%) of <u>on source</u> coverage was obtained in the optical region of the spectrum. The Vela satellites were in the proper orbital position for X-ray observations of Sco X-1 for a total of 78 hours (13% of the total program), 67 hours (11%) of which overlapped with optical observations. The X-ray measurements consisted of one-second samples obtained approximately every minute, resulting in a total of 1.3 hours (0.2%) <u>on source</u> coverage. These data are presented in Section II with a discussion of the various observational techniques employed. Correlations between X-ray and optical flux measurements are presented in Section III, and flux histograms are discussed in Section IV.

A complete listing of the raw data in the form of page print-outs, microfilm, or magnetic tape is available on a limited basis to workers in this field. Inquires should be directed to J. P. Conner at Los Alamos Scientific Laboratories.

II. The Data

Figure 1 presents the observed B magnitudes, the X-ray intensity, and an X-ray spectral hardness index as functions of Universal Time.

a) Optical Observing Techniques. The local standard star and the differential photometric tenchique used in previous monitoring of Sco X-1 (see, for example, Hiltner and Mook 1967) were employed. All optical sites but Tokyo and Leiden Southern Station employed photoelectric UBV photometers, UBV standard stars and standard reduction techniques. When data from more than one site overlap, good agreement is generally found between independent sets of data (for example, on 5/17 and 5/2 in Figure 1). All of the optical sites were given equal weight in the averaging process to be discussed in Section III.

Data from Tokyo were photographic photometric observations as described in Osawa, Ichimura, and Tomita (1971). Periods of overlapping observations with other sites show good average agreement within the large scatter inherent in the technique of photographic photometry.

Observations from the Leiden southern station were made on the Walraven five-color photometer, the B band of which is sufficiently close to the B band of the UBV system that no transformation was judged necessary to convert the differential Walraven B magnitudes to those of the UBV system. The good agreement between the Leiden data and overlapping UBV observations from other sites demonstrates the validity of this simplification.

Some aspects of the optical observations shown in Figure 1 have been previously published. The Tokyo data appear in Osawa et al. (1971). The relation between optical brightness and Walraven color resulting from the Leiden data has been discussed by Mook, Messina, Pel and Hiltner (1974). The

color data from the CTIO observations appear in Mook, Blanco, Hesser, Kunkel and Lasker (1972).

b) The X-Ray Observations. The X-ray data from each of the four Vela spacecraft were collected simultaneously in two photon energy channels of approximately 3 to 6 kev and 3 to 12 kev. A detailed description of the X-ray instrumentation on board the spacecraft may be found in Conner, Evans and Belian (1969). In Figure 1, the quantity X = -2.5 Log (3 to 12 kev photon count rate) has been plotted versus Universal Time so that the X-ray and optical flux measurements are directly comparable. The period of rotation of each spacecarft was approximately one minute. The field of view was restricted by collimators to six degrees to that Sco X-1 was observed effectively for one second out of every minute; this is why, as noted in Section I, the X-ray flux was monitored for a period of 78 hours during this program and of this time 1.3 hours were effectively spent on source.

The hardness ratio, R, plotted in Figure 1 is the count rate observed in the 6 to 12 kev energy channel divided by that observed in the 3 to 12 kev channel.

Corrections for source-detector aspect have been applied to the X-ray data, but all data for which this multiplicative correction factor was larger than 3.0 were rejected. This rejection threshold is admittedly arbitrary but was consistently applied. It should be noted that the hardness ratio is independent of aspect corrections.

The X-ray detectors exhibited significant differences in calibration, and, in addition, the individual calibrations depended on the detector operating temperature. During the period of the World Wide Watch, the variation of the angle between the incident solar radiation and the spin axis of the satellite

caused appreciable changes in detector temperature. Both the sensitivity and the hardness ratio measurements of all detectors have been normalized by assuming that the average behavior of the source was the same for four approximately equally-spaced detector temperature intervals. This normalization process may obscure some real variations of the emission intensity but, in view of the known existence of the variations in detector responses, was considered preferable to not applying any corrections for these effects.

Other experiments (e.g., Burginyon, Grader, Hill, Price, Rodrigues, Seward, Swift, Hiltner and Mannery (1970)) have shown that a bremsstrahlung spectrum is observed for Sco X-1 in the X-ray energy range considered here. The measured spectral responses of the X-ray detectors on board the spececraft were folded with bremsstrahlung spectra of plasmas at various temperatures to generate the hardness-to-temperature and the count-to-energy flux conversion relations shown in Figure 2.

III. Correlations Between Observable Properties of Sco X-1

Among the three quantities plotted versus UT in Figure 1, (that is B, X and R), there are three correlations to discuss.

a) X vs. B. Previous correlations between X-ray and optical flux have been discussed by Gursky (1973), Burginyon *et al*. (1970) and Conner, Evans, Belian, Strong, Hiltner and Kunkel (1970). The present data were discussed in a very preliminary form by Hiltner (1973) and in a more refined stage by Conner, Belian, Evans, Strong, Mook and Messina (1973). The present data and those from UHURU represent the most extensive published studies of this object to date.

Figure 3 is a plot of one minute averages of overlapping B and X measurements obtained in this study (similar plots employing longer averaging intervals show the same general character). The clumping of the optical data around three preferred brightness states is typical of Sco X-1 [see the discussion of brightness histograms for Sco X-1 in Hiltner and Mook (1970a); the histograms for the present data are discussed in Section IV]. Except for the photographic data, individual optical observations have typical standard deviations of $\pm 0^{m}.02$ or less. The absolute accuracy of the X-ray intensity data is about 30 percent but the relative accuracy is considerably better with photon count statistics of typically 4 to 6 per cent standard deviation.

The data presented by Gursky (1973) and the preliminary reconnaissance of the present data by Hiltner (1973) suggested that high values of X-ray intensity ($X < -7.0$) occured only when $B \leq 12.7$, that is, when Sco X-1 was brighter than the optical "flare threshold" discussed by Hiltner and Mook (1967, 1970a,b)

This result, if correct, suggests an association between the phenomenon triggering optical flaring and that triggering large X-ray flux output. Also, the earlier results indicated that the mean brightness of the X-ray intensity increased with decreasing optical brightness. Figure 3, however, shows a relation between X and B in partial contradiction to these two earlier conclusions and the data presented by Bradt et al. (1974) and Canizares et al. (1974). It should be pointed out that the X-ray observations corresponding to a B magnitude near 13.5 were all made in a single passage of one satellite where a significantly large normalization factor was applied in computing the X-ray intensities. On the basis of the present data, prima facae for about 90% of the time of simultaneous X-ray and optical observations, Sco X-1 shows $\chi < -7$ when $B \leq 12^{m}_{\cdot}7$. Since the data presented by Gursky (1973), Bradt et al. (1974), Canizares et al. (1974) involve a substantially shorter period of observation than that represented here, our result is not necessarily inconsistent with these other studies except for the low X-ray intensities near magnitude 13.5. On the other hand, the 90% figure should be treated with caution. Of the time X-ray data showed $X < -7$ only slightly more than half was covered optically. Additional overlapping X-ray and optical data could have altered the 90% estimate significantly.

b) X vs. R. Previous correlations between X-ray spectral hardness (temperature) and X-ray intensity have been published, the most recent and extensive

being that by Canizares et al. (1973).

Figure 4 presents the results of the present study, which is similar in appearance to Figure 2 of Canizares et al. (1973). There is a more or less symmetrical distribution of points for most of the data, but a definite indication of an extension of the distribution to higher X-ray intensities and hardness ratios is evident. This correlation was also obtained by Evans et al. (1970) on the basis of limited data for Sco X-1. The sense of the relation is what would be expected for a bremsstrahlung source, viz., the hardness (or temperature) is higher for higher intensity. However, the observed slope is larger than that expected for the flux variation to be due only to variations in temperature of an optically thin isothermal plasma, which indicates an increase in the emission measure at increased temperature.

c) R vs. B. Figure 5 shows one-minute averages for R and B during times of simultaneous X-ray and optical observations of the source. There is no apparent correlation of the variables plotted.

A search of the data shown in Figure 1 was made to investigate whether a systematic difference in R exists for optical flare and nonflare states. No differences were found. Similarly, there is no evidence for a difference in behavior of hardness ratio during times of X-ray flux activity. This situation is similar to that for the wavelength dependence of the optical variations (Mook et al. 1972a). Regardless of the nature of the optical variations (flare, flickering, or more gradual changes), the wavelength dependence of the emission is observed to be the same.

IV. Some Statistics of the Observations

Sco X-1 is variable in flux at all observed wavelengths. In this section we consider first the presence or absence of any periodic variation and then two related questions: What was the nature of any preferred states of flux output from Sco X-1 during this program? And, how long and in what manner should the flux from this variable object be sampled in order to obtain a statistically meaningful sample of its behavior?

a) Nature of Variation. There have been many attempts to establish a periodicity for the variable magnitude of Sco X-1. (i.e., van Genderen, 1969). The present data were also inspected for any possible periodicity. An early inspection of Figure 1 revealed two essentially identical variations at 1970 May 3.97 and 1970 May 11.86, a separation of 7.89 days. These two rises from a B mag of 13.2 to about May 12.6 are spectactularly similar, including a glitch on the two rising branches. There were no optical observations 7.9 days earlier or later than the two above dates. With the announcement of a 3.9 day period by Lyretyj and Efremov (1974) it was noted that this reported period is nearly 0.5 that of the two observed changes of state observed on 1970 May 3 and 11. Consequently, the observations were plotted with both a period of 3.931 days and 7.89 days. Neither showed any periodicity, but were essentially scatter diagrams. The phase of the two changes of state is near .22 when computed by the elements given by Lyutyj and Efremov (1974). Evidence for a periodic variation of Sco X-1 still remains obscure. [See also Messina (1974) for radial velocity observations.]

b) B-Magnitude Histograms. Figure 6 is a histogram of the number of times (30 second integrations) Sco X-1 was observed to be within a given interval

of B magnitude during the course of this program (i.e., in Figure 1). Three peaks are seen at B ~ $12^{m}.6$, $12^{m}.9$, and $13^{m}.5$ corresponding to the propensity of Sco X-1 to emit at these three magnitude levels during this program. These preferred levels are reflected in the clumping of average points seen in Figure 3, and they fall near (but do not always coincide with) magnitudes at which peaks occur in previous histograms for Sco X-1, (see Figure 7). During some periods of observing, one or more of these peaks have been absent, and the relative heights of the peaks have been different. The fact that some peaks continue to appear at roughly the same magnitudes, however, suggests the possible persistency of these favored states of brightness for a time interval of years. Hiltner and Mook (1970a,b) have pointed out that if their yearly histograms represent valid samples of a true parent distribution of brightness states for each year, then the histograms of Figure 7 demonstrate a temporal variation in the parent distribution of energy output. On the other hand, it is unknown how long one must sample the flux from Sco X-1 to obtain a significant sample of the parent distribution.

c) Completeness of Coverage From Different Optical Observing Sites. Because this program was able to operate around the clock for 25 days, and because different observing sites provided varying degrees of coverage, some conclusions may be reached regarding the significance of statistical results for Sco X-1 which are based on limited observing periods. Table II presents some details of the optical coverage during this program for each of the participating sites. The coverage represented by the histograms of Figure 4b are included for comparison. Figure 8 shows the B-magnitude histograms obtained at each of the participating sites.

A comparison of Figures 6 and 8 shows that different optical sites obtained different brightness histograms during the coures of this program.

The coverage of Sco X-1 by Hiltner and Mook in 1967, 1968 and 1969 shown in Table II is certainly no better than the coverage represented by the sites taking part in the present study. This means that the samples of data given by Hiltner and Mook (1970a,b) are probably not representative of a true parent distribution and therefore, it is difficult to draw significant conclusions concerning time variablilty.

Figure 9 is the X-histogram for all the X-ray data combined. There are no distinct multiple peaks as is the case for the optical histograms, but the X-histogram does show a high-intensity "tail". In 1971 October and November Canizares <u>et al</u>. (1973) also observed a high intensity tail in the X-ray intensity distribution.

Figure 10 shows the X-histograms obtained by the individual satellites. The variability between "observing sites" is not so great as for the optical case. This could be due in part to the normalization process described, but some differences remain.

The existence of large differences in behavior of X-ray emission at different times is most clearly demonstrated by considering adjacent observing periods of the same pair or satellites having the same normalization factors for both periods. Such an example is shown in Figure 12 where the X-histograms for satellites 5A and 5B are given for 1970 May 12-13 and 1970 May 17. The difference in behavior for these two periods is also very evident in Figure 1.

V. The Relation of Sco X-1 to Other Optically Identified X-ray Sources. Suggestions for Further Work.

Sco X-1 was the first extrasolar X-ray source to be discovered and the first stellar X-ray source to be optically identified (Giacconi, Gursky, and Van Speybroeck 1968). In the recent past a number of other optical counterparts have been identified, including a number of binary star systems (Gursky 1973). Interest seems to have turned to this class of objects. We wish to emphasize the fact that the properties displayed by Sco X-1 continue to stand alone. There is no definitive observational evidence for its membership in a binary system, thus leaving the energy generating mechanism an open issue. The ratio of optical to X-ray flux is much smaller in Sco X-1 than in any of the known binary systems. In fact, the optical and infrared radiation is so small that self-absorption must be introduced in order to bring this region of the spectrum into agreement with the X-ray bremsstrahlung spectrum. The irregular photometric behavior and variable brightness distribution are also unusual. While some of the binary sources show dramatically variable spectra (for example, 2U1700-37 and 0900-40 -- see Boley and Mook 1973) no other source yet studied presents such bewildering variations in the optical line spectram coupled to (and often in correlation with) large, irregular photometric activity (Mook, Edwards and Hiltner 1972a). In many respects, this source remains the most exciting because so little is understood of its basic nature.

It seems clear from our discussion in Section IV that little is to be

gained by further programs of simultaneous broad-band X-ray and optical flux measurements such as the one presented here. However, we would like to strongly encourage observational efforts along several other lines to complement and extend our present body of knowledge of Sco X-1. We note with regret that the complexity of the properties this source displays has discouraged workers in both X-ray and optical astronomy from continuing to gather meaningful data. The demanding question of the relationship between this source and binary sources will only be settled through further vigorous accumulation of data along the following lines:

a) X-ray spectral information correlated with optical flux measurements, especially information (even upper limits) on X-ray line emission.

b) High resolution optical spectra; the line profiles are complex and time variables (Messina 1974; Mook et al. 1972b), and only high dispersion spectra will permit an untangling of the various features and a thorough investigation of possible periodic radial velocity variations, the existence of which would lead to the establishment of limits on orbital motions present in the system. The complex radial velocity variations reported by Westphal, Sandage and Kristian (1968) and Messina (1974) provide a clear incentive for further work in this area; indeed, radial velocity analysis of the optical lines may be the only effective technique of establishing the binary (or multiple) nature of the object.

c) Low dispersion, high time resolution spectra simultaneous with X-ray observations to permit study of the coupling between X-ray flux level and excitation state in the line-emitting region.

d) Simultaneous X-ray and/or optical coverage with radio observations to determine the relationship between the complex radio structure and the better-known X-ray and optical properties of this object. In particular, the relation between the radio emission and the hard X-ray component deserves attention (Ramaty, Cheng and Tsuruta 1974).

This list is not meant to be comprehensive. The items given, however, seem to be the most pressing to the present authors.

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TABLE I

Participants in the 1970 World Wide Watch on Sco X-1

Institution	Observers	Apparatus
Mauna Kea Observatory University of Hawaii, USA	Mook	24-inch reflector, single channel photometer with 1P21, analog output, B-magnitudes
Leiden Observatory Southern Station, Africa	Pel and Hiltner	36-inch reflector, Walraven five color photometer, Walraven magnitudes (Walraven, T. and Walraven, J. H. 1960; Rijf, Tinbergen, and Walraven 1969)
Cerro Tololo InterAmerican Observatory, Chile	Blanco, Hesser, Kunkel, and Lasker	36-inch reflector, dual channel photometer with 1P21's pulse counting (Lasker 1971, 1972), Band V-magnitudes
Kitt Peak National Observatory, Arizona, USA	Golson	36-inch reflector, 50-inch reflector, single channel photometer with 1P21, DC integrator, B-magnitudes
Siding Spring Observatory, Australia	Stokes (assisted by Mr. Vinco Ford on some observations)	16-inch reflector, single channel photometer with 1P21, DC integrator, B-magnitudes
Dodaira, Japan	Tomita, Shibasaki, Satō, Nakagiri	50-cm Nikon Schmidt, 1 minute exposures on Fuji FL-OII emulsion through an L-39 filter
Okayama, Japan	Osawa, Ichimura, Noguchi, Norimoto, Watanabe	30-cm reflector with reducing camera, 10 minute exposures on 103a-O emulsion through a L-39 filter
Los Alamos Scientific Laboratory Los Alamos, New Mexico, USA	Conner, Belian, Evans, Strong	Vela 5A, 5B, 6A, 6B Spacecraft, 3-6 kev and 3-12 kev NaI(TL) Scintillation detectors

TABLE II

Coverage of Sco X-1 By Participating Optical Observatories

Site	Hours on Source	% of 225 hr Program	Days on Which Observations were made	% of 25 day Program
Cerro Tololo	44.3	20%	10	40%
Australia	24.2	11%	6	24%
Hawaii	52.2	23%	17	68%
Kitt Peak	52.3	23%	14	56%
Leiden	47.4	21%	17	68%
Japan			10	40%
Hiltner & Mook 1967	42.1*		20	
Hiltner & Mook 1968	22/22**		7/8	
Hiltner & Mook 1969	50/25**		12/6	

* very broken coverage over a 60^{d} interval

** two runs separated by about a month

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Figure Captions

Figure 1. The Observations. Top Half: A schedule of the observations. For each observing location or spacecraft, a symbol appears at each time an observation was made. Lower Half: A time history plot of all optical and X-ray data. The ordinates are defined in the text. All normalizations and corrections discussed in the text have been applied. One minute averaging of the data has been performed. Satellite 6909 = 5A, 6911 = 5B, 7033 = 6A, and 7044 = 6B.

Figure 2. Plot of the count-to-energy flux conversion factor, K, and the hardness ratio, R, vs. spectral temperature for a thermal bremsstrahlung spectrum. The experimentally determined spectral response and resolution characteristics of the X-ray detectors were employed in the calculation.

Figure 3. One minute averages of simultaneously observed values of B vs. X, for all of the data shown in Figure 1.

Figure 4. One minute averages of simultaneously observed values of X and R for the data shown in Figure 1b.

Figure 5. One minute averages of simultaneously observed values of R and B for the data shown in Figure 1b.

Figure 6. B magnitude brightness histograms for Sco X-1. N is the number of times (30 second integrations) Sco X-1 was observed to have a B magnitude within the range indicated.

Figure 7. B magnitude brightness histograms of the same type as in Figure 6 for the years 1967-1969 (Hiltner and Mook, 1970a).

Figure 8. B magnitude histograms for Sco X-1 obtained at each of the sites participating in this program.

Figure 9. X histograms for the X-ray data obtained in the World Wide Watch. N is the number of times (unaveraged) Sco X-1 was observed to have a value of X within the range indicated. X = -2.5 log (count rate of 3 to 12 kev photons).

Figure 10. X histograms for Sco X-1 obtained with each of the Vela satellites.

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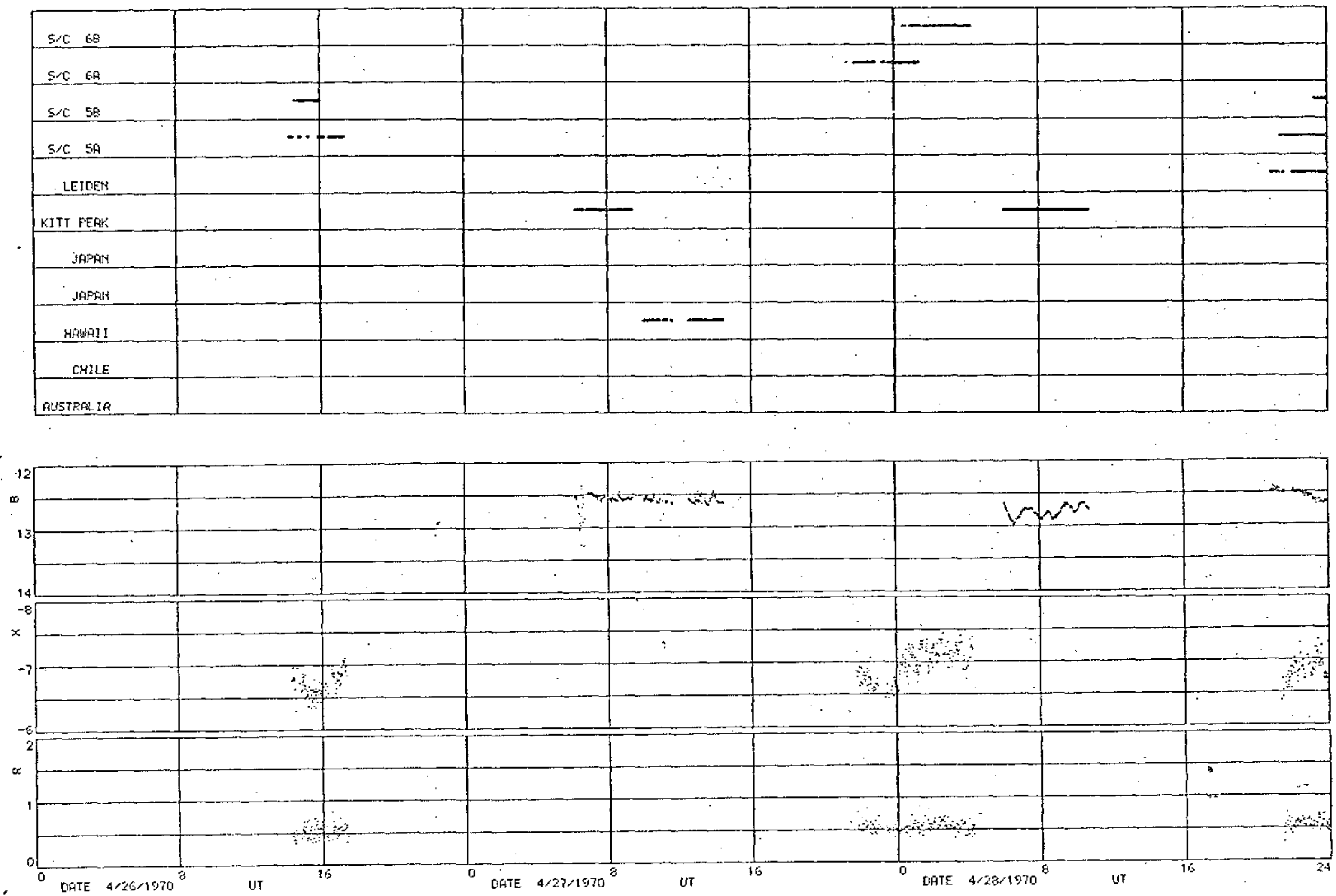
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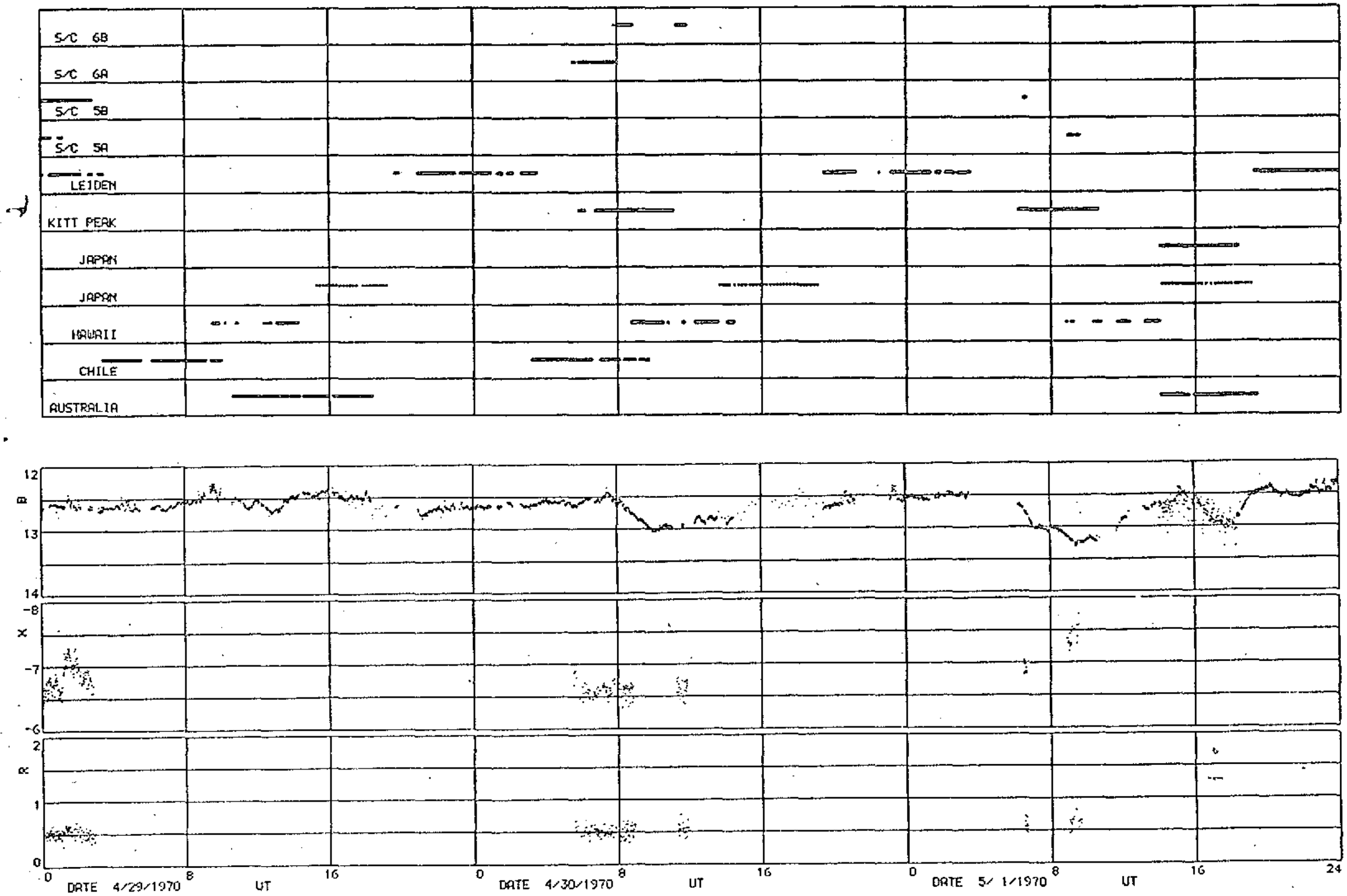
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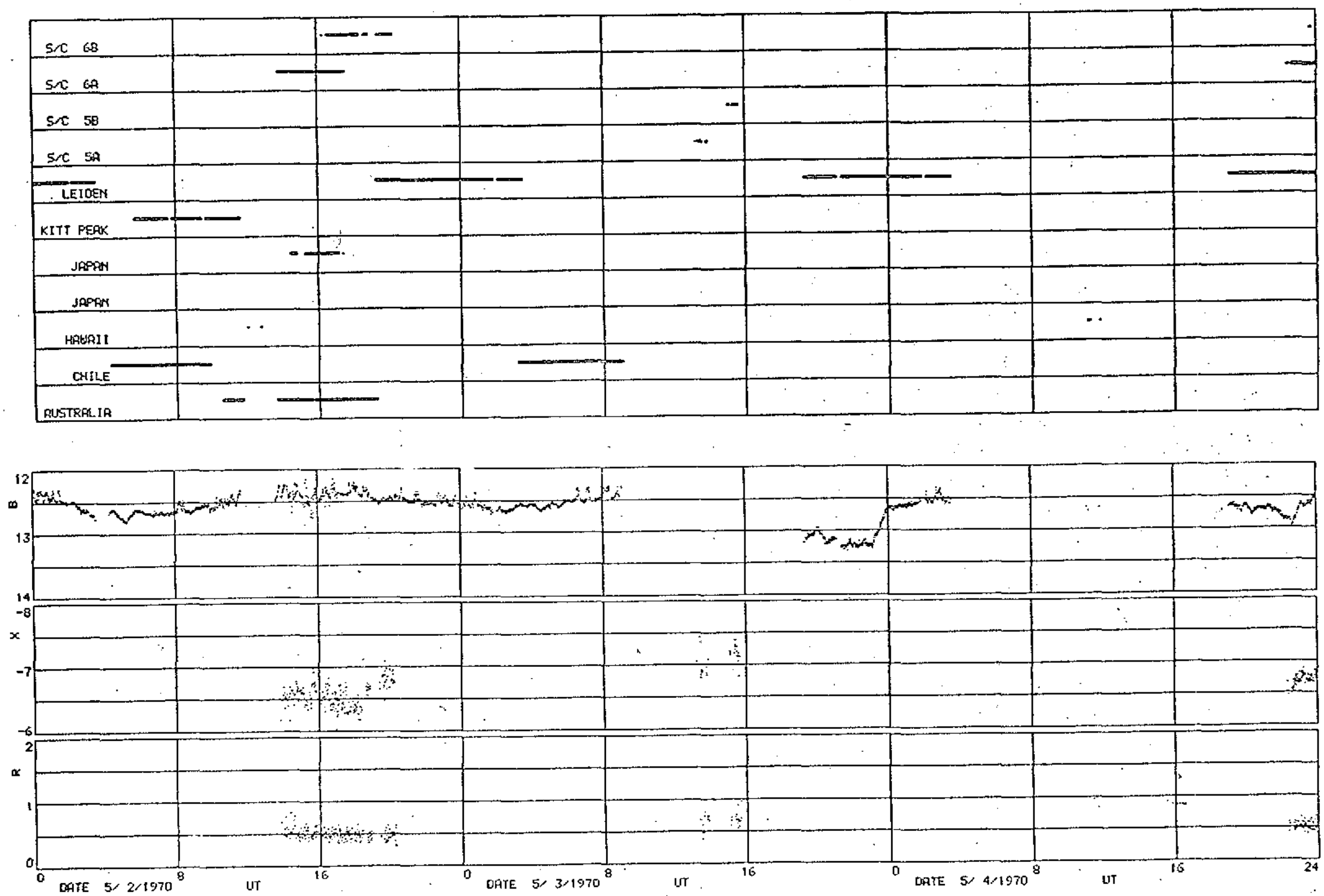

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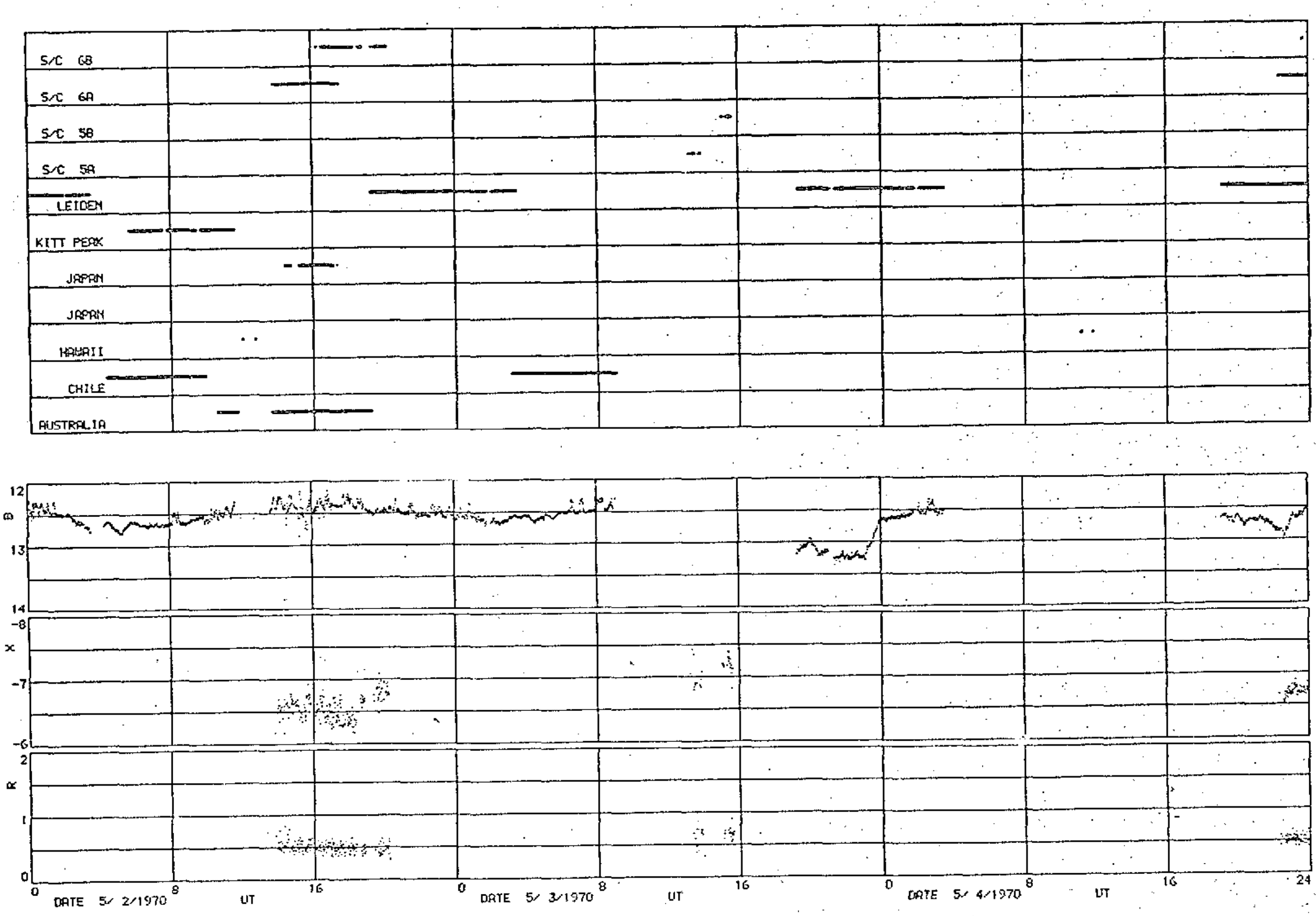

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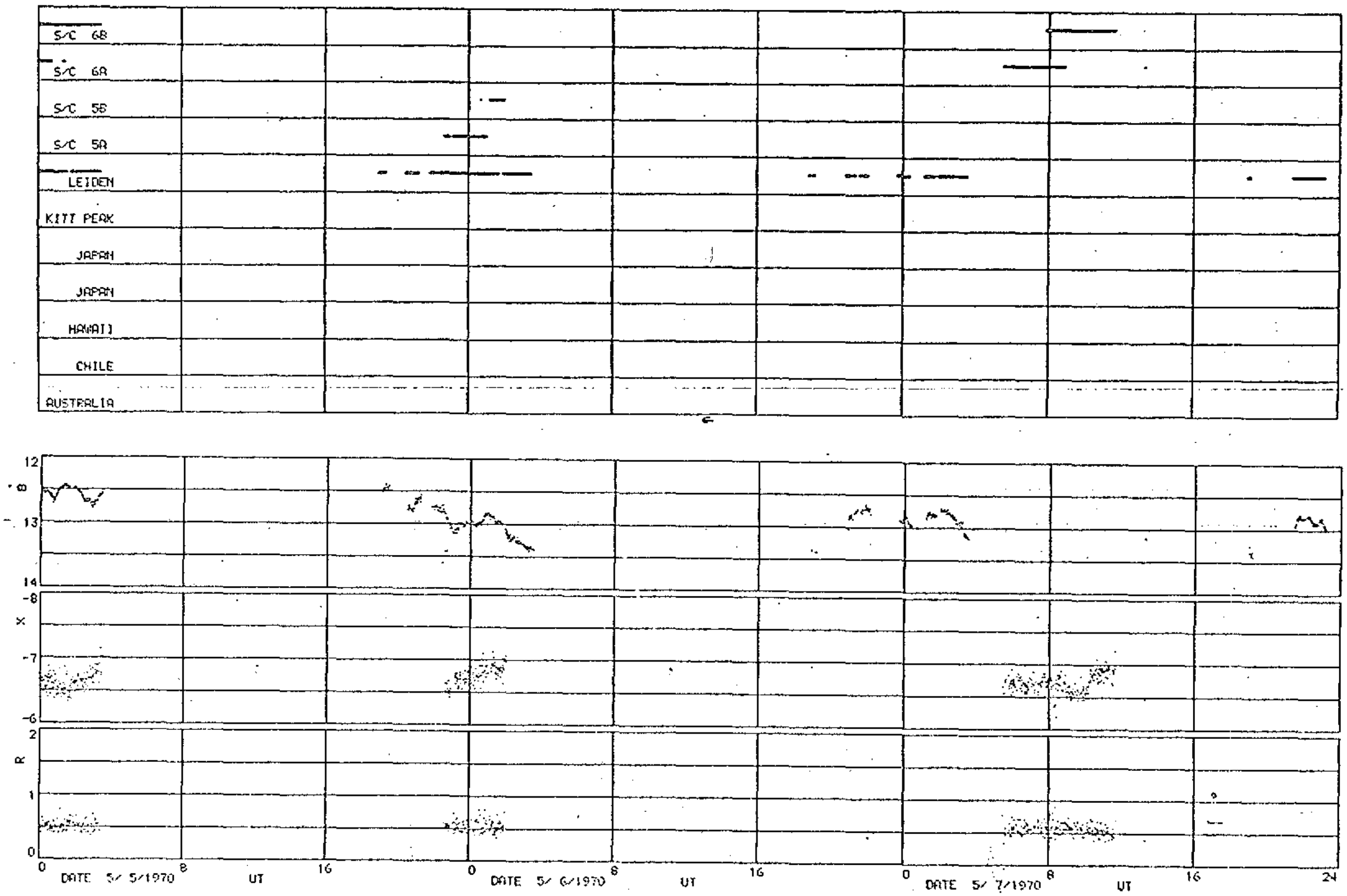
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X
-8
-7
-6
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1
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DATE 5/ 5/1970
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UT
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DATE 5/ 6/1970
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UT
16
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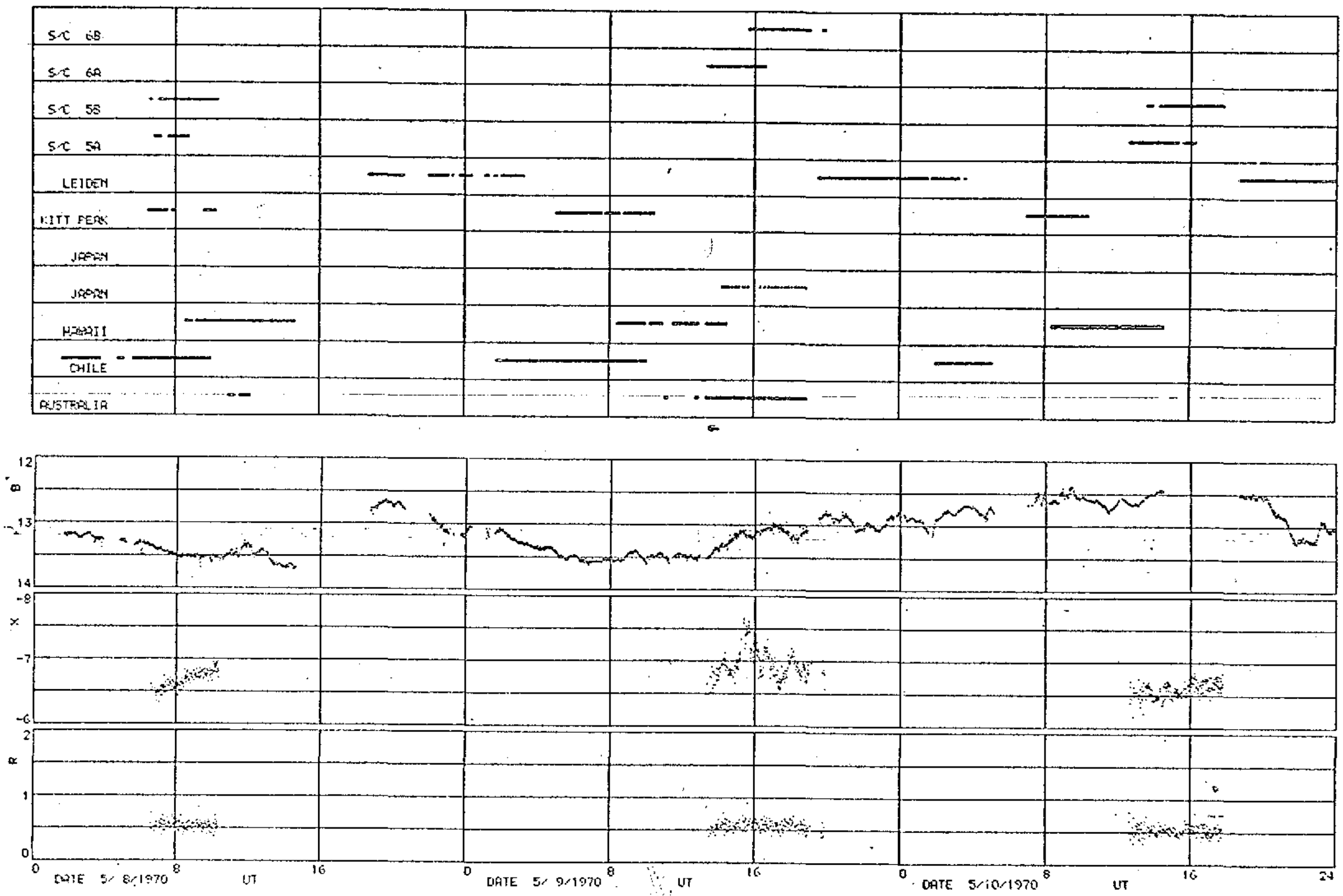
DATE 5/ 7/1970
8
UT
16
24



S/C 6B
S/C 6A
S/C 5B
S/C 5A
LEIDEN
KITT PEAK
JAPAN
JAPAN
HAWAII
CHILE
AUSTRALIA
B
12
13
14
X
-8
-7
-6
R
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DATE 5/ 8/1970
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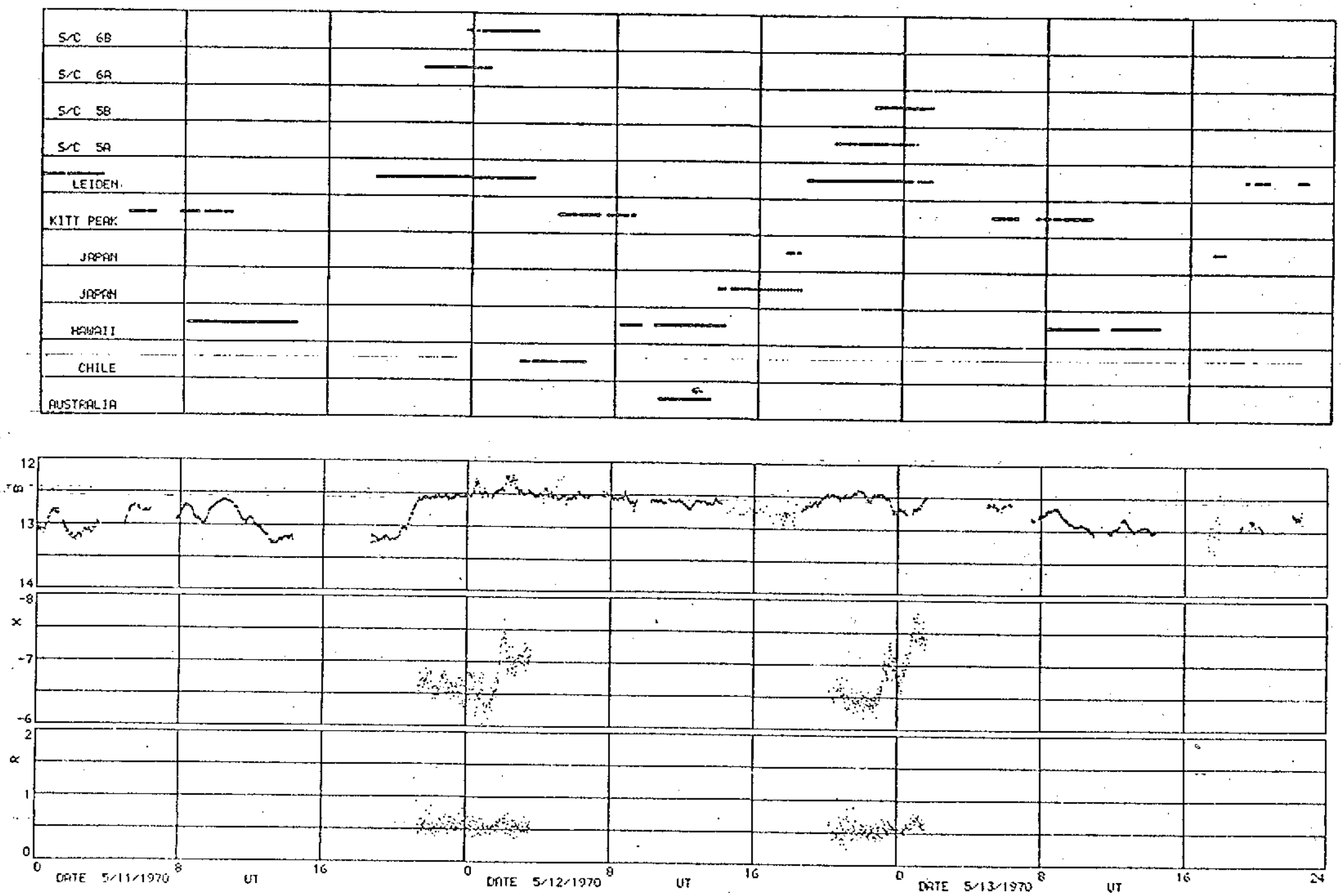
DATE 5/10/1970
UT

24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HAWAII
CHILE
AUSTRALIA
12
13
14
-8
x
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2
α
1
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0
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DATE 5/12/1970
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DATE 5/13/1970
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UT
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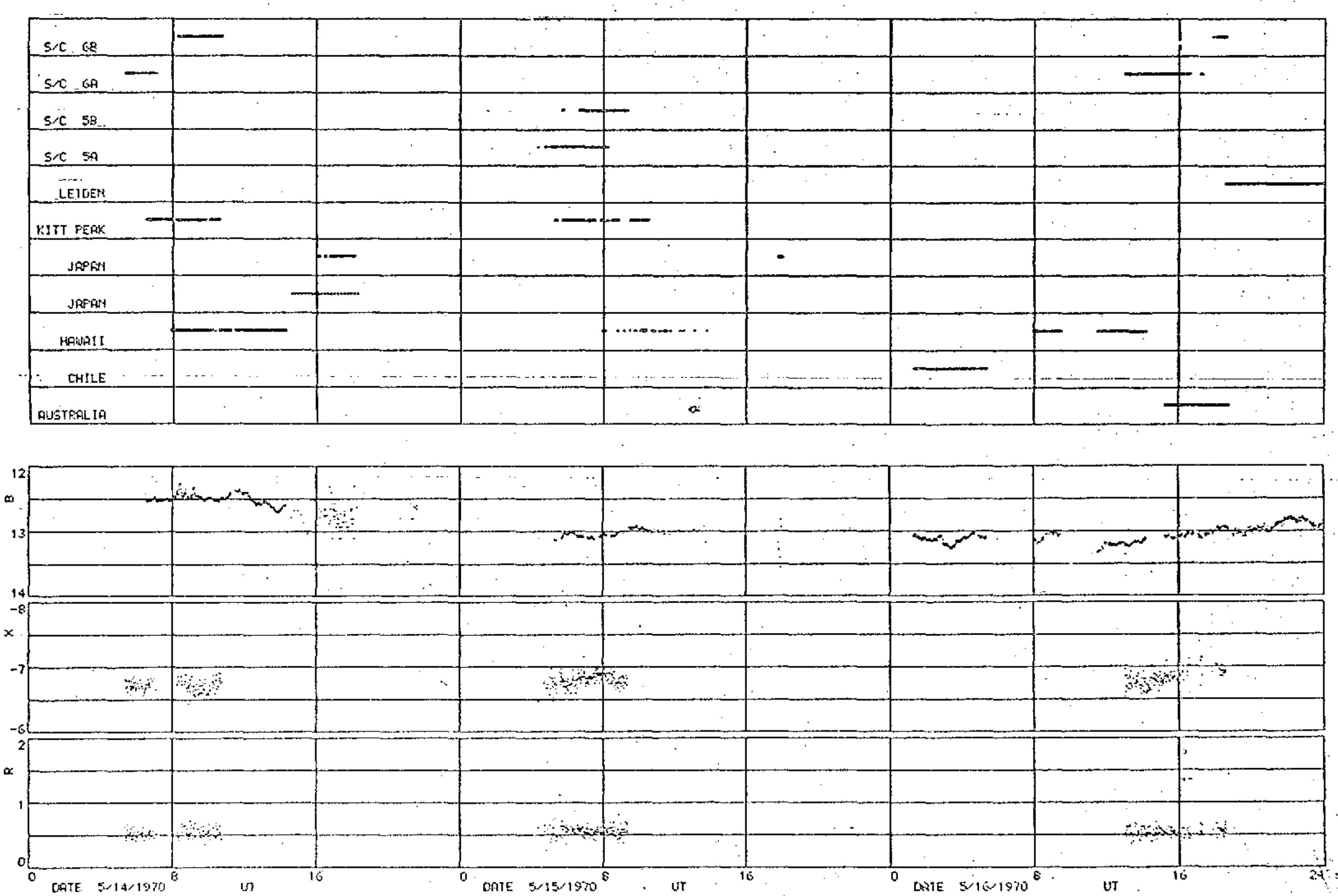
25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AUSTRALIA
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14
-8
X
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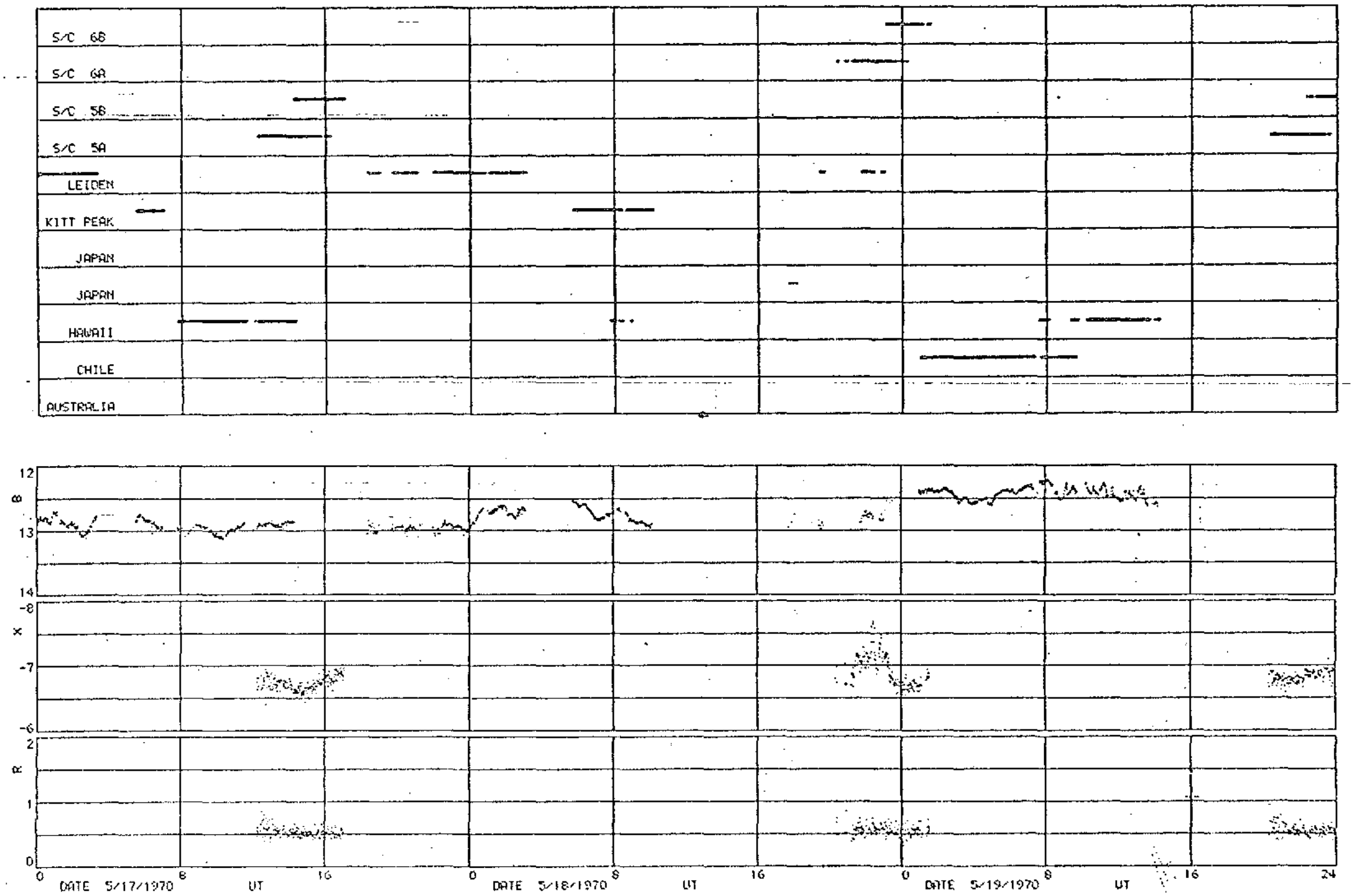
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B
12
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14
X
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DATE 5/17/1970
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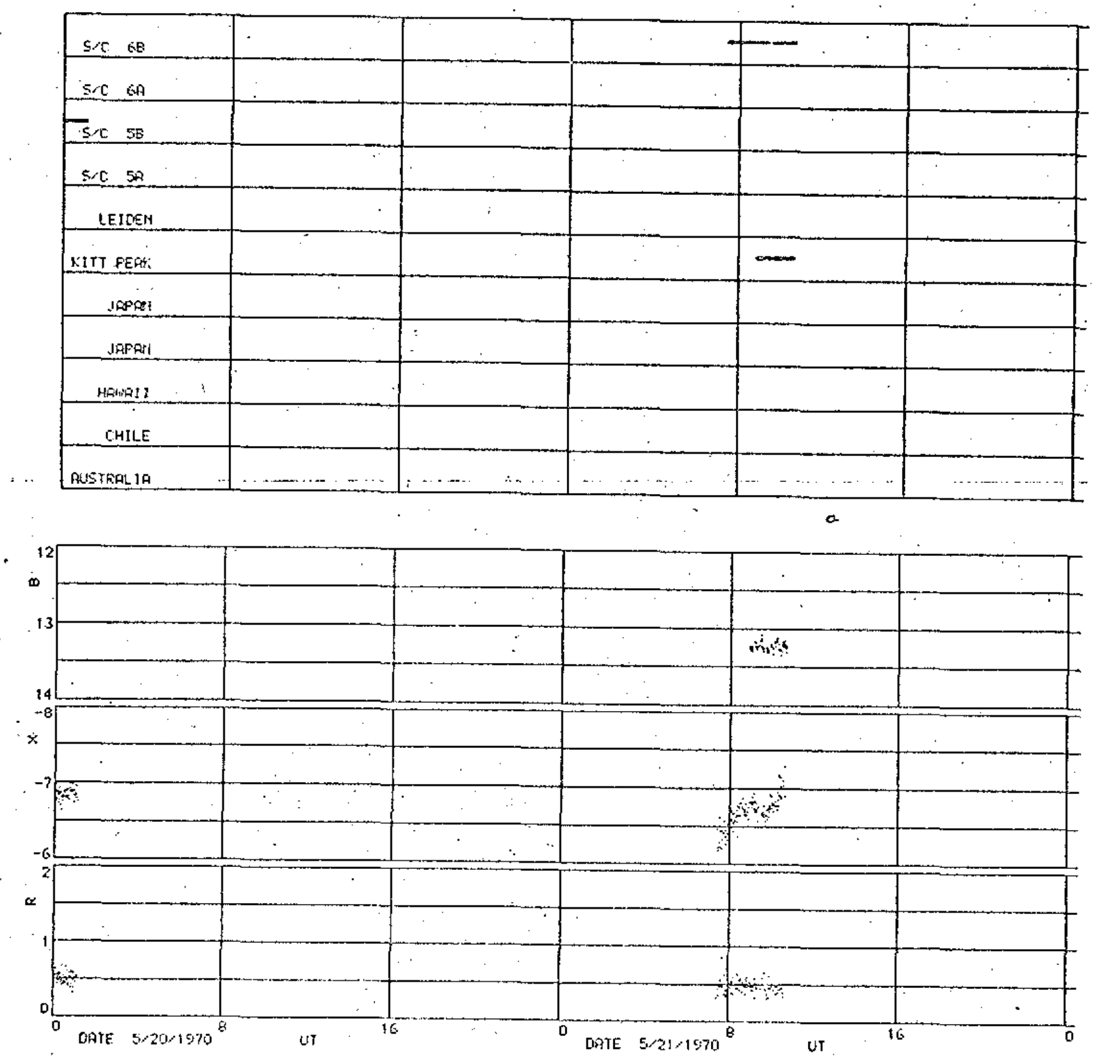
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B
12
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14
X
-8
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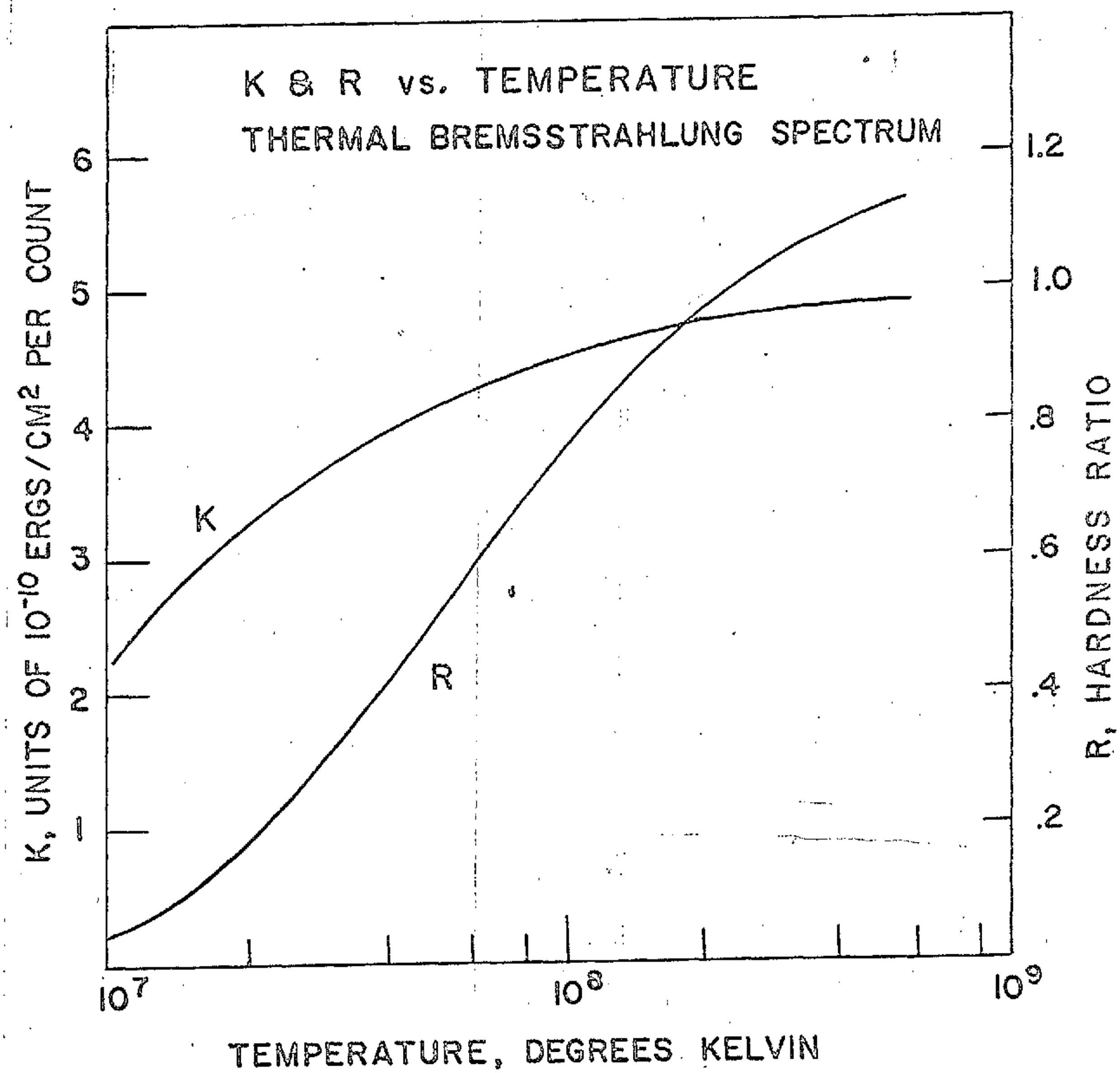
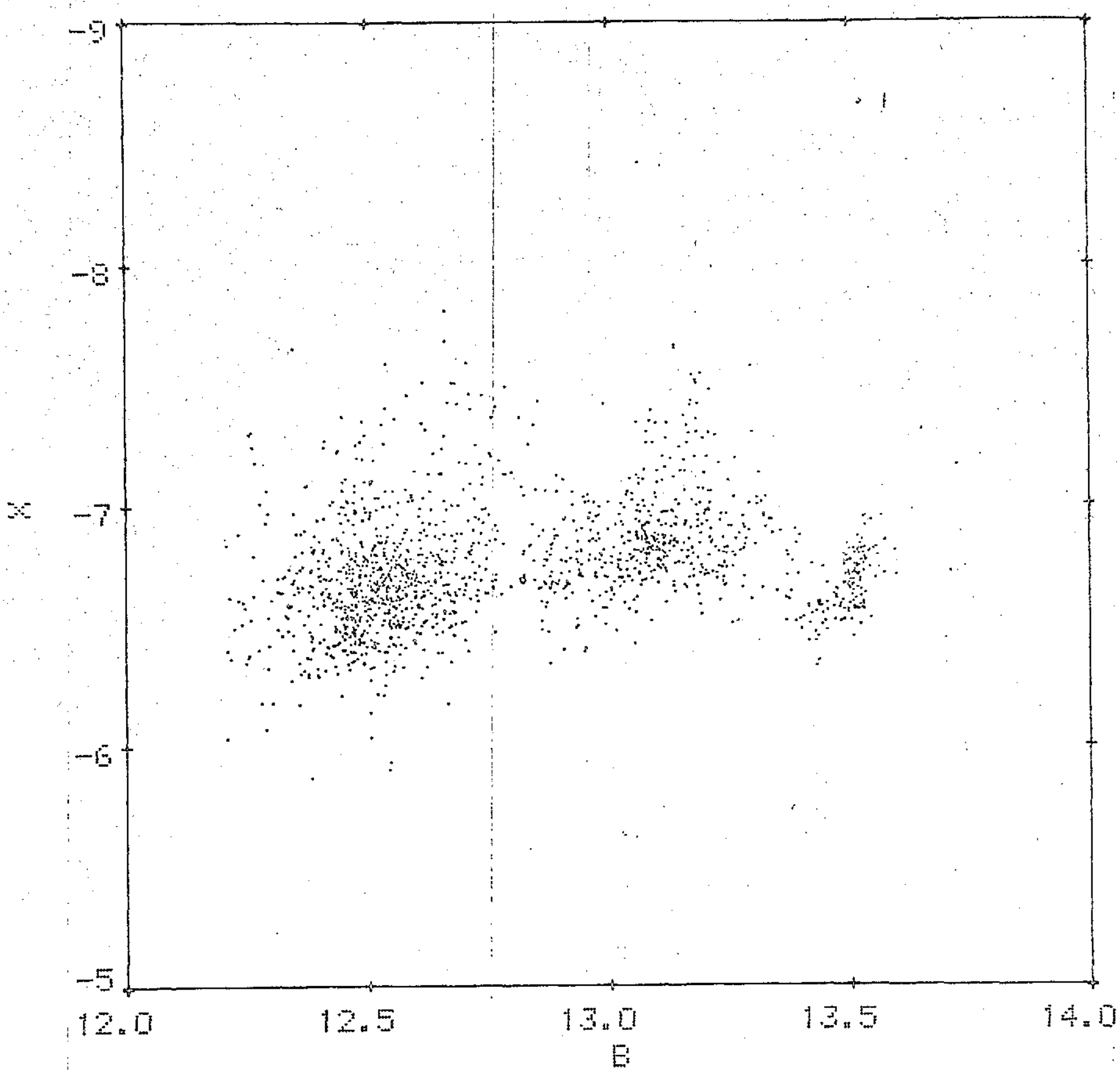
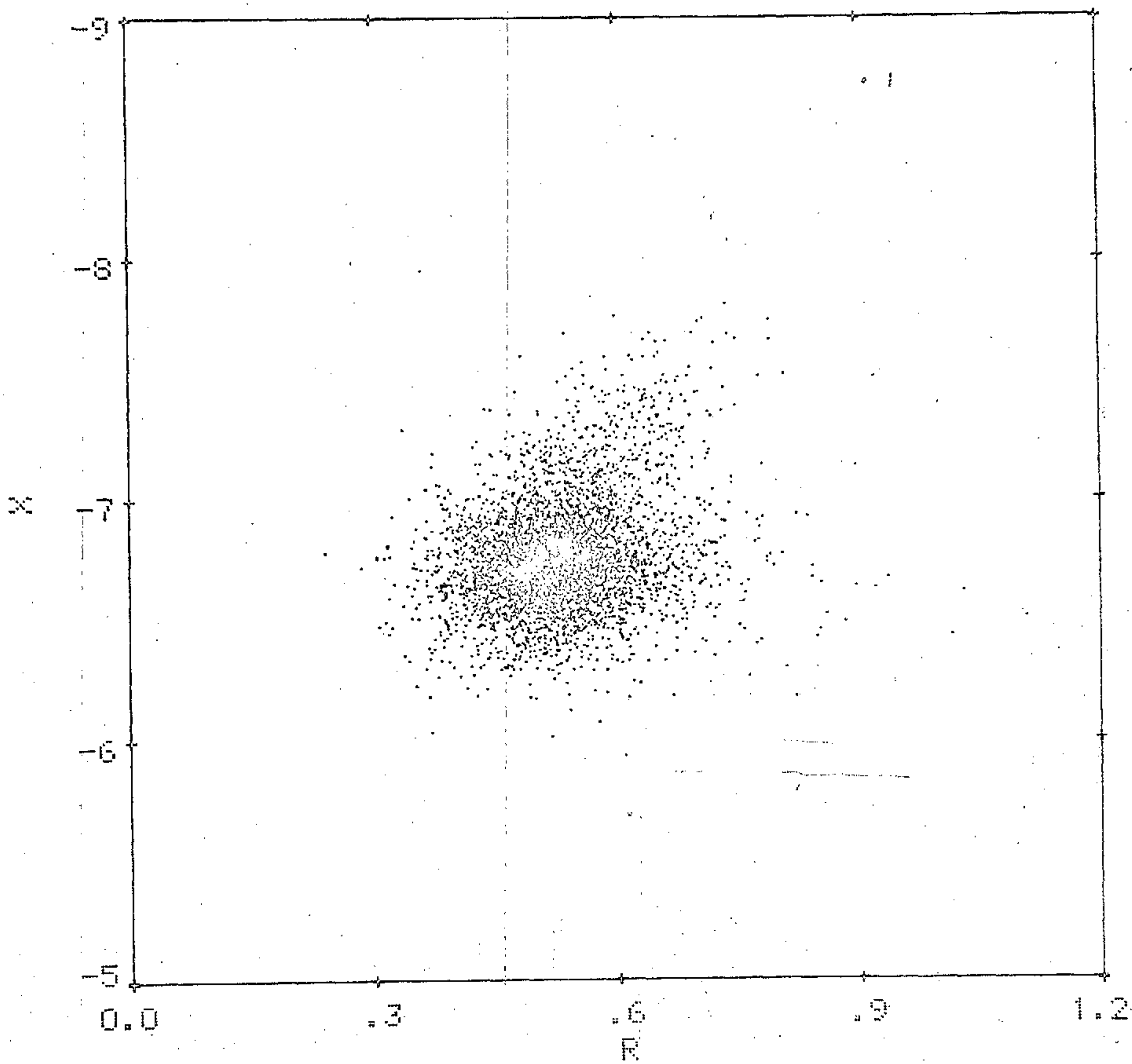
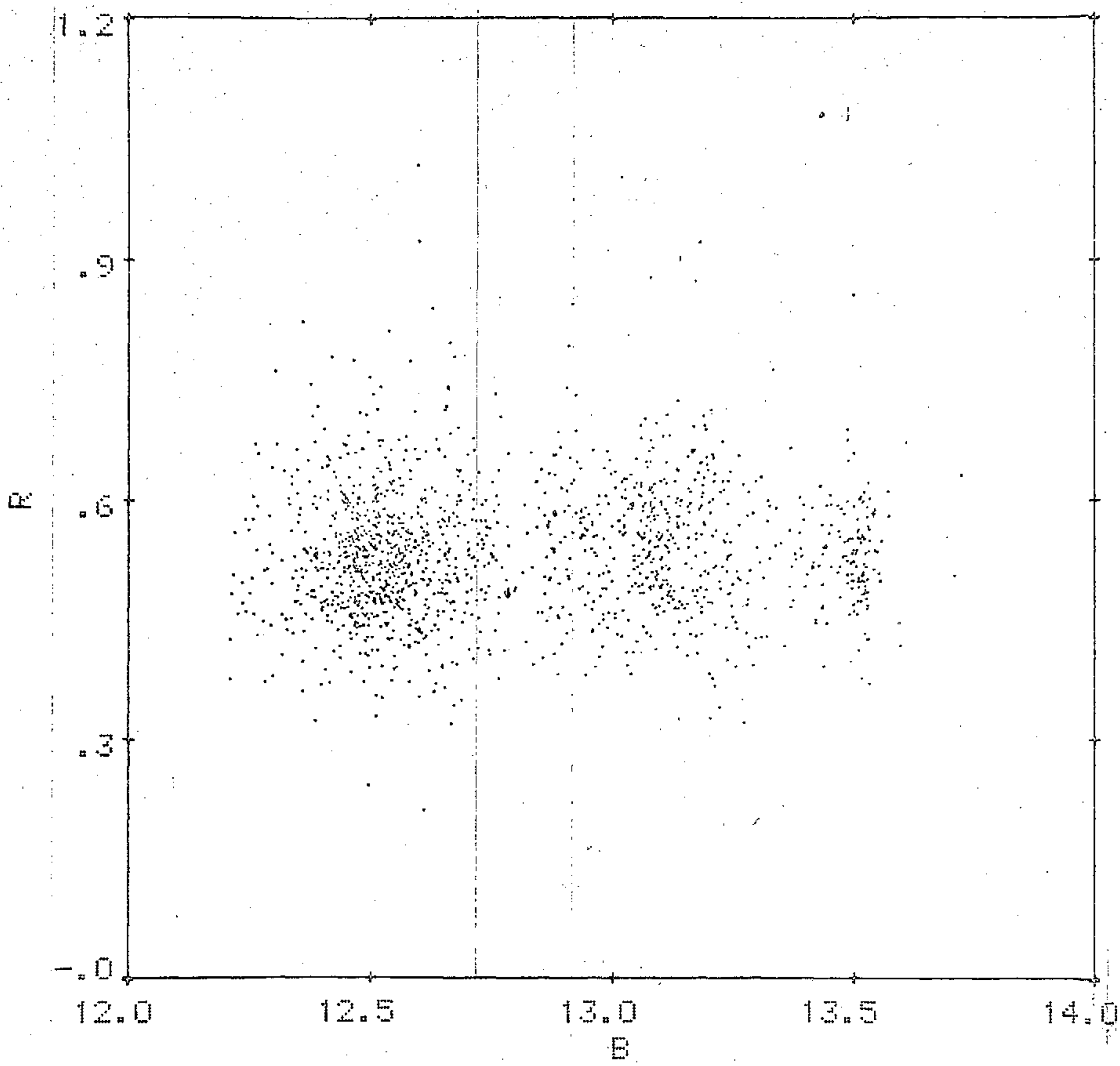
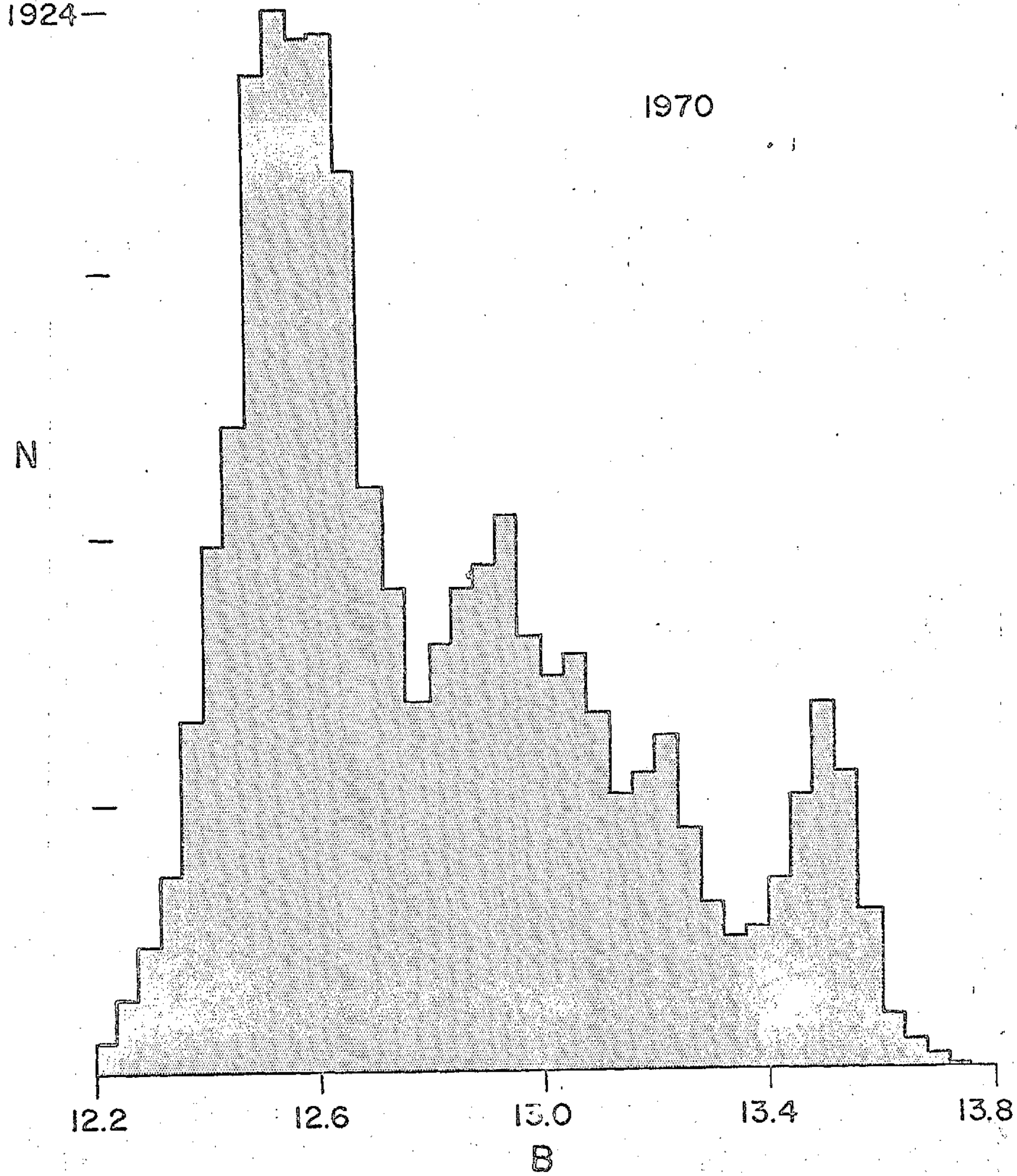

K & R vs. TEMPERATURE
THERMAL BREMSSTRAHLUNG SPECTRUM
K
R
K, UNITS OF 10^{-10} ERGS/CM^2 PER COUNT
R, HARDNESS RATIO
1
2
3
4
5
6
.2
.4
.6
.8
1.0
1.2
10^7
10^8
10^9
TEMPERATURE, DEGREES KELVIN

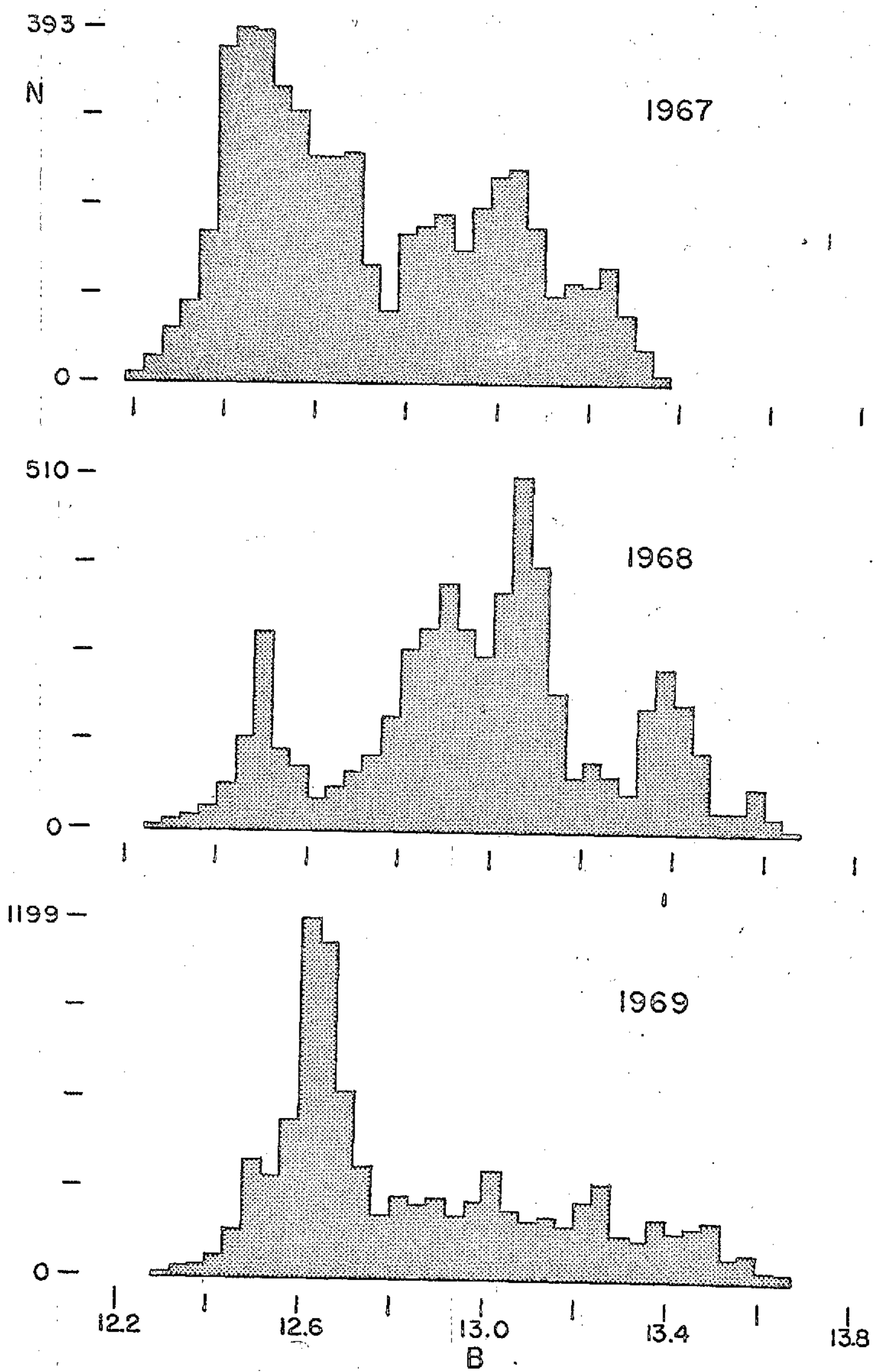


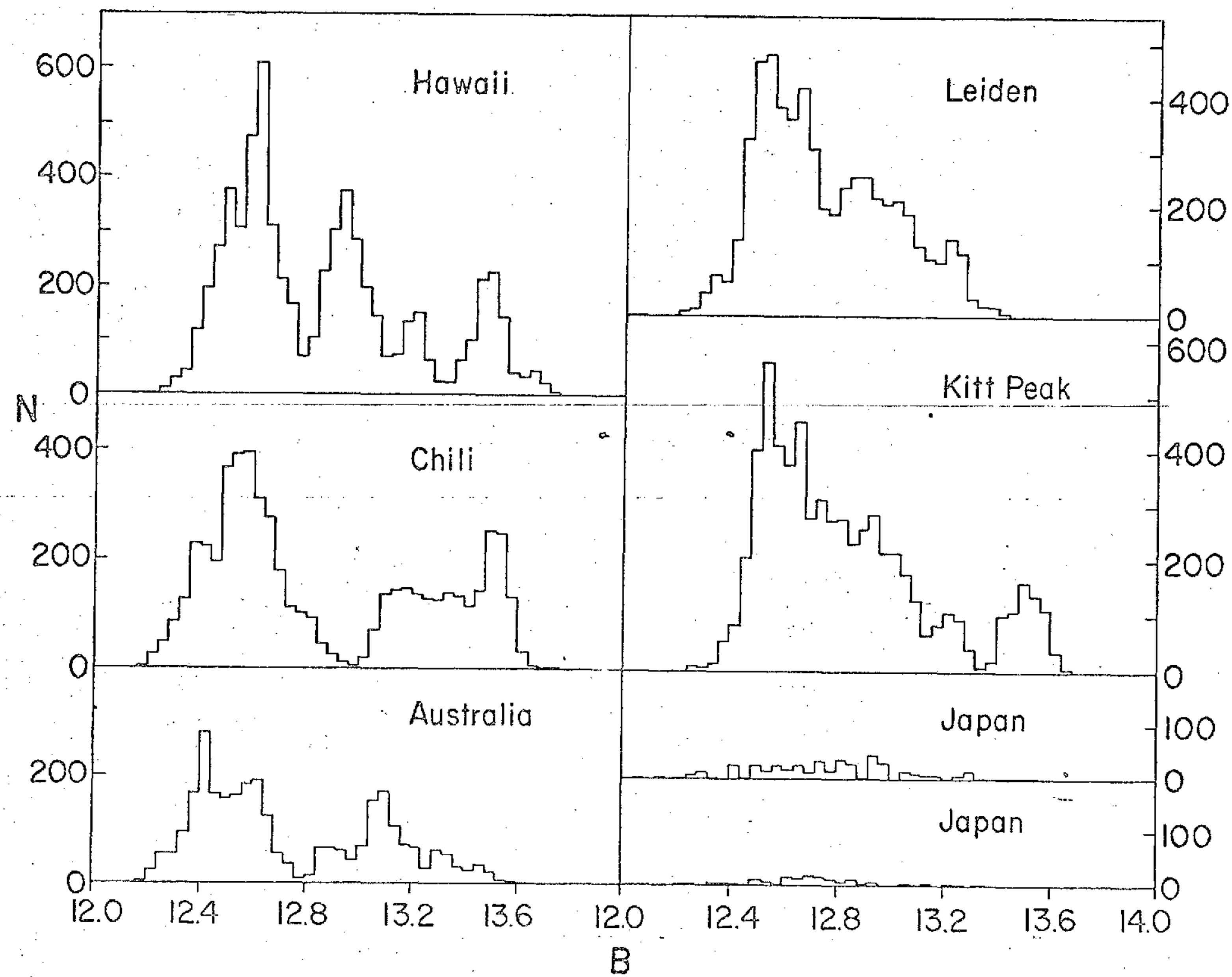
-9
-8
-7
-6
-5
x
12.0
12.5
13.0
13.5
14.0
B


-9
-8
-7
-6
-5
x
0.0
.3
.6
.9
1.2
R

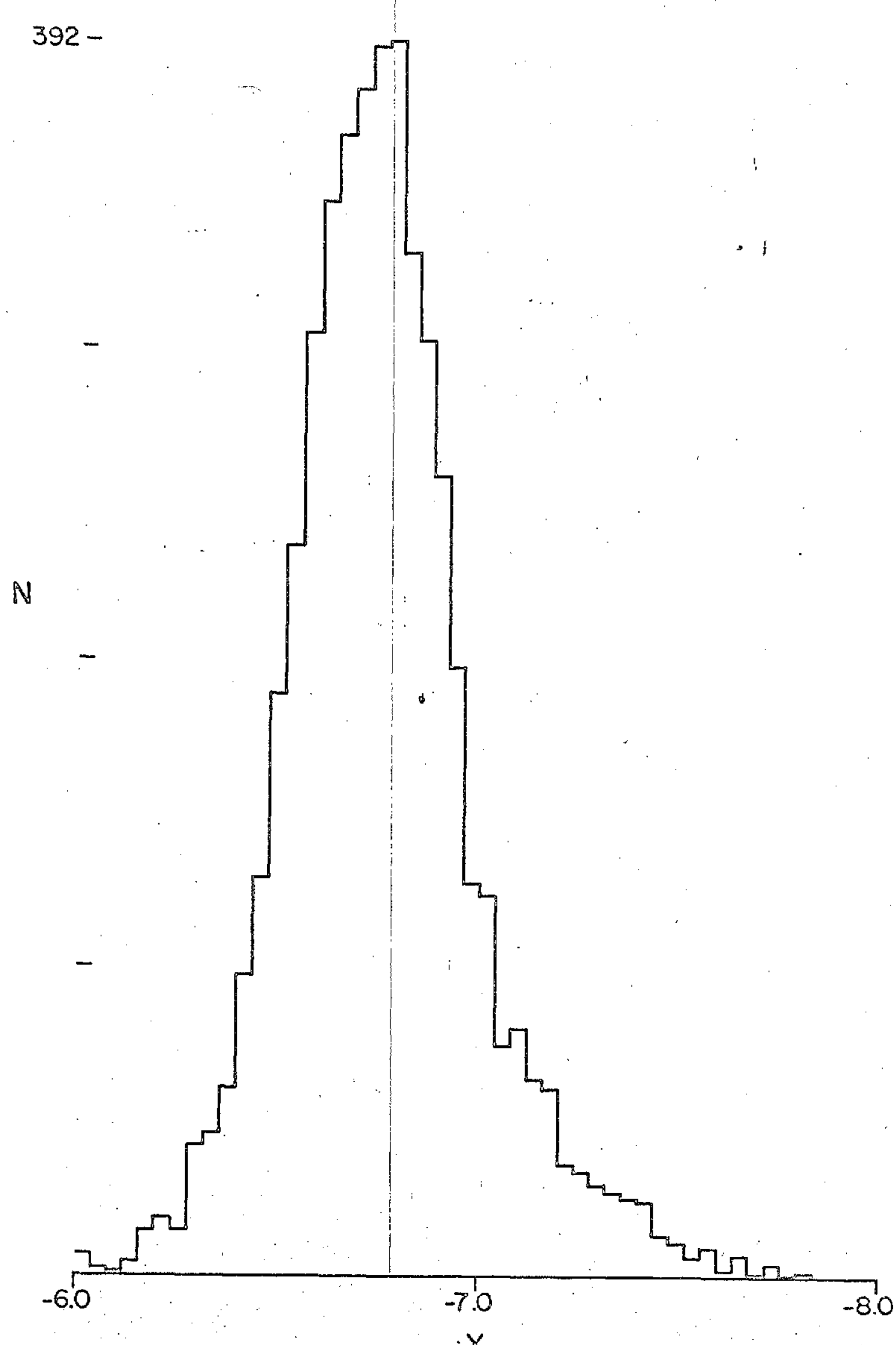

1.2
.9
.6
.3
-.0
R
12.0
12.5
13.0
13.5
14.0
B

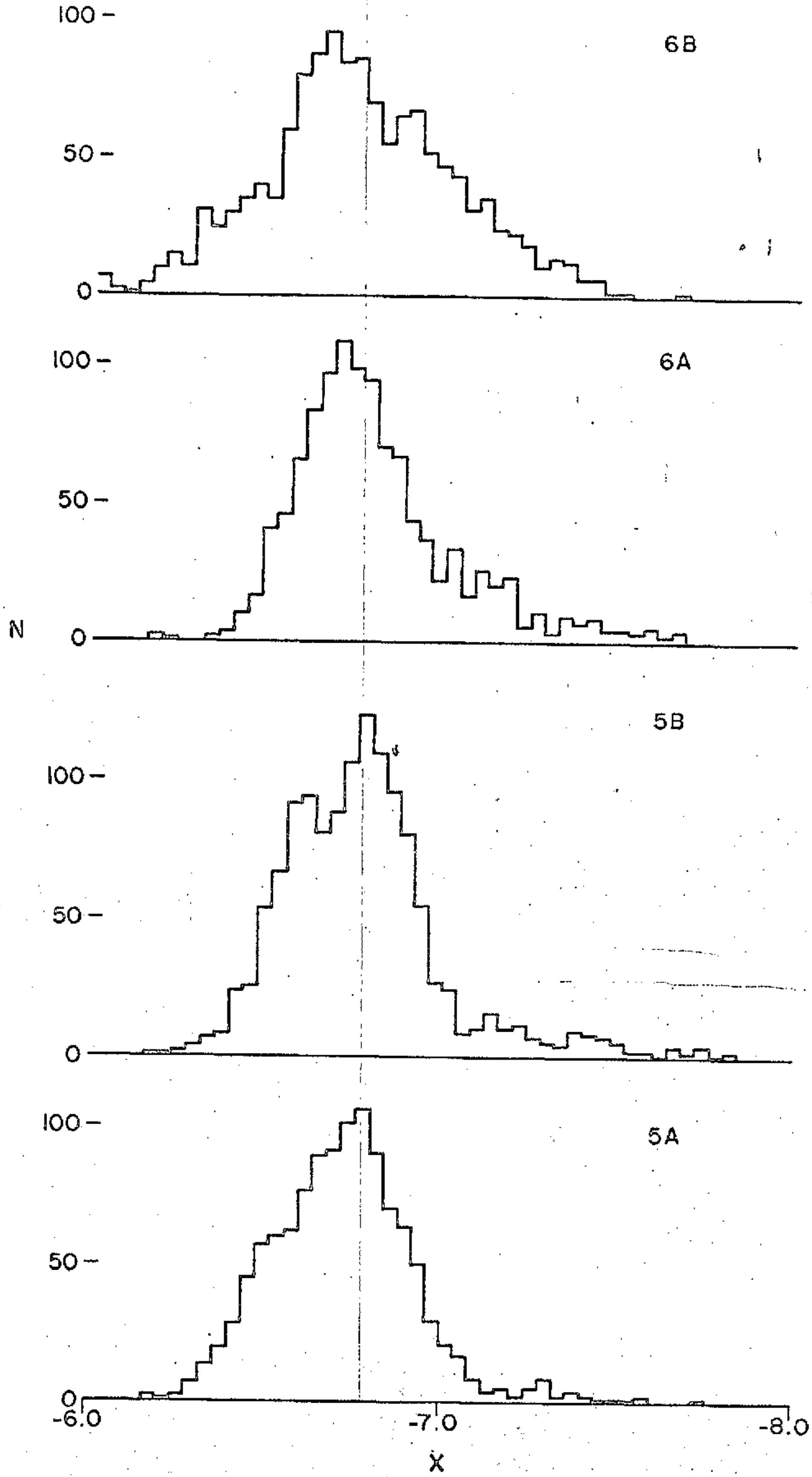

1924
1970
N
12.2
12.6
13.0
13.4
13.8
B


393
N
1967
0
510
1968
0
1199
1969
0
12.2
12.6
13.0
13.4
13.8
B


Hawaii
Leiden
Chili
Kitt Peak
Australia
Japan
Japan
N
B
0
200
400
600
100
12.0
12.4
12.8
13.2
13.6
14.0

35


392
N
-6.0
-7.0
-8.0
X


6B
6A
5B
5A
100
50
0
N
-6.0
-7.0
-8.0
X